ν_τ detection and the IDS-NF baseline

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We discuss the physics case for an emulsion cloud chamber (ECC) for ν_τ detection at a neutrino factory at an intermediate baseline, $L \simeq 4\,000$ km, or at the long baseline, $L \simeq 7500$ km. We conclude that the physics potential of the present design of τ-detectors is not sufficient to justify its inclusion in the IDS-NF baseline setup. On the other hand, we recommend further investigation of the detector technology, since oscillation into ν_τ could be important to pin down new physics scenarios.

I. STANDARD OSCILLATION PHYSICS

The prime focus of a neutrino factory is to provide precision measurements or tight constraints on the three-flavor oscillation parameters. Many studies done in the context of the ISS [1, 2] show that the potential to achieve this is excellent if it is ensured that parameter correlations and degeneracies can be resolved. Any single rate measurement at some fixed baseline L and neutrino energy E is sensitive only to a *combination* of parameters. To measure all parameters separately, the following possibilities exist to resolve the correlations and degeneracies:

- **Use measurements at different energies.** This is difficult at a neutrino factory due to the limited width of the neutrino spectrum and the limited energy resolution of the MIND detector. It has been shown that the energy resolution of MIND is not enough for a single detector located at intermediate baseline to solve all of the degeneracies.

- **Perform measurements at two different baselines L_1 and L_2.** This is an extremely powerful possibility, which is the reason, it is included in the current IDS-NF baseline setup. In particular, a measurement at the magic baseline [3] turns out to be very important. A detailed optimization study for L_1 and L_2 has been performed in [4], with the result that the combination $L_1 = 4\,000$ km, $L_2 = 7\,500$ km is optimal to study standard oscillation physics as well as non-standard neutrino interactions.

- **Study different oscillation channels.** With MIND detectors, the Golden ($\nu_e \to \nu_\mu$) and Disappearance ($\nu_\mu \to \nu_\mu$) channels are available, while an inclusion of a ν_τ detector could in addition provide a window on the Silver ($\nu_e \to \nu_\tau$) and Discovery ($\nu_\mu \to \nu_\tau$) channels. Ref. [4], however, shows that the combination of one MIND detector and one ECC at the intermediate baseline is not as good as the combination of two MINDs at two baselines, mainly because of the very low statistics at the τ-detector for $\theta_{13} \leq 2°$. On the other hand, adding one ECC to the setup with two MINDs does not provide more than a marginal gain in sensitivity, independently of the neutrino energy and baseline. The reason is that the analytical expressions for the oscillation probabilities in the Golden and Silver channels are very similar (they differ only in the signs of certain terms and in the exchange $\sin\theta_{23} \leftrightarrow \cos\theta_{23}$ in several others), so that the Silver channel could help only to resolve degeneracies. This, however, is already done by the combination of the two Golden channel detectors. We, also, have checked numerically that also the inclusion of the Discovery channel does not improve the sensitivity of the neutrino factory to standard three-flavor oscillations.

  In Ref. [5], the silver channel was studied to solve the octant degeneracy and as a tool to study deviations from maximality of the atmospheric angle θ_{23}. A comprehensive study of alternatives to the silver channel for these tasks is lacking, see Ref. [6]. A likely outcome of such a study will be that alternatives are better than the silver channel. However, in the absence of such a study, we cannot draw a firm conclusion.

As for the standard three-family oscillations, we thus believe that an ECC detector able to look for $\nu_e \to \nu_\tau$ and $\nu_\mu \to \nu_\tau$ channels will not improve significantly the performances of the baseline neutrino factory setup with two MINDs , due to the strong statistical limitations of the present detector design and to the relatively limited number of parameters to be measured.

II. NON-STANDARD OSCILLATION PHYSICS

There are several interesting cases of new physics that can be studied through neutrino oscillation experiments. We will address here the potential of a detector capable of τ-identification in searching for Non-Standard Interactions (NSI) or additional singlet fermions with some admixture with the three-family left-handed neutrinos, so-called "sterile neutrinos".

Non-standard interactions are effective four-fermion interactions, which arise if neutrinos couple to new, heavy particles. This is similar to the Fermi theory of nuclear beta decay emerging as the low-energy fingerprint of the Standard Model weak interactions. NSI can affect the neutrino production and detection mechanism if they are of the charged current type, and the neutrino propagation if they are of the neutral current type. In the first case, the NSI can be parametrized as a small admixture of the "wrong flavor" $|\nu_\beta\rangle$ to a neutrino produced or detected in association with a charged lepton of flavor α:

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^s_{\alpha\beta}|\nu_\beta\rangle, \qquad \text{e.g. } \pi^+ \xrightarrow{\varepsilon^s_{\mu e}} \mu^+\nu_e \tag{1}$$

$$\langle\nu^d_\alpha| = \langle\nu_\alpha| + \sum_{\beta=e,\mu,\tau} \varepsilon^d_{\beta\alpha}\langle\nu_\beta| \qquad \text{e.g. } \nu_\tau N \xrightarrow{\varepsilon^d_{\tau e}} e^- X\,. \tag{2}$$

The second case corresponds to a non-standard contribution to the MSW potential:

$$\tilde{V}_{\rm MSW} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix}\,. \tag{3}$$

In the above expressions, the parameters $\varepsilon^{s,d,m}_{\alpha\beta}$ give the strength of the NSI relative to standard weak interactions. A generic estimate is

$$|\varepsilon^{s,d,m}_{\alpha\beta}| \sim \frac{M^2_{\rm W}}{M^2_{\rm NSI}}\,, \tag{4}$$

where $M_{\rm NSI}$ is the new physics scale, at which the effective NSI operators are generated. Even though the present model independent bounds on the $\varepsilon^{s,d,m}_{\alpha\beta}$ are not very strong ($\mathcal{O}(0.1-1)$). However, these bounds are not likely to be saturated in specific models [7, 8]; at least if one follows the usual guidelines of model building: no fine-tuning, as few new particles as possible, new physics preferably at or above the TeV scale, *etc.* Indeed, if the estimate (4) is taken at face values, with $M_{\rm NSI} \sim 1$ TeV, we expect $\varepsilon^{s,d,m}_{\alpha\beta} < 0.01$. It is important to keep in mind that, in any specific model, the phenomenological parameters $\varepsilon^{s,d,m}_{\alpha\beta}$ will in general not be independent.

Phenomenological models in which N new singlet fermions are mixed with the three left-handed ones imply a straightforward generalization of the PMNS matrix to a $(3+N)\times(3+N)$ unitary mixing matrix, that for the case of $N=1$ is:

$$U_{\rm PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \tag{5}$$

Some of these elements are strongly constrained by non-observation at reactors and at the MiniBooNE experiment. On the other hand, models in which the mixing angles θ_{i4} between a new singlet fermion ν_s and the three active ones are all very small cannot be excluded. Notice that, both for NSI and sterile neutrino models, new CP-violating phases are present in addition to the standard three-family oscillation phase δ.

A. NSI in production and detection

NSI in production and detection imply non-unitarity of the PMNS matrix. Therefore, if some of the new parameters $\epsilon^{s,d}_{\alpha\beta}$ are non-vanishing, it is not enough to study the two channels available at the MIND detector (the $\nu_e \to \nu_\mu$ golden channel and the $\nu_\mu \to \nu_\mu$ disappearance channel) to measure all of the new parameters of the model. To study non-unitarity of the leptonic mixing matrix, there are two options:

- Measure all the oscillation probabilities $P(\nu_\mu \to \nu_e)$, $P(\nu_\mu \to \nu_\mu)$, $P(\nu_\mu \to \nu_\tau)$ (or $P(\nu_e \to \nu_e)$, $P(\nu_e \to \nu_\mu)$, $P(\nu_e \to \nu_\tau)$, and check if they sum up to unity. A problem of this approach is that ν_e detection is very difficult in a MIND detector, so either there will be large uncertainties or a secondary detector with a different technology (for example, liquid argon) should be added to the two MINDs setup. Moreover, the systematical errors in the different oscillation channels will be different, which also limits the achievable sensitivity.

- Use neutral current events. This is also difficult [9], and, at present, only a sensitivity at the ten per cent level can be achieved. This might improve if the neutral current cross sections were known better and if more sophisticated event selection criteria could be developed.

Most of the new parameters could be measured using a dedicated near detector. The detector design should be optimized so as to measure as much oscillation channels as possible, and with very good τ-identification capability. Therefore, this detector cannot be a scaled version of MIND. At present, no detailed study of such a detector has been performed, see Refs. [7, 8] for the potential of an ECC near to a Neutrino Factory source and the recent Ref. [10].

B. NSI in propagation

NSI in propagation do not imply a non-unitary PMNS matrix. In this case it is therefore possible to obtain information on all of the new parameters $\epsilon^m_{\alpha\beta}$ using the two channels available at the MIND detector.

A detailed study of NSI in propagation at a neutrino factory has been presented in Ref. [4] (see fig. 1, taken from that paper). The results obtained show that the IDS-NFS baseline neutrino factory with two MIND detectors at $L \sim 4000$ km and $L \sim 7500$ km is sensitive to $\varepsilon^m_{\alpha\beta} \sim 0.01 - 0.1$, independent of whether a ν_τ detector is present. There might be a physics case for this detector if the process $\nu_\tau + N \to \tau + X$ proceeds in an unexpected way (e.g. an anomalous energy dependence), if τ leptons are produced in a non-standard way (e.g. $\varepsilon^d_{e\tau} \neq 0$ or $\varepsilon^d_{\mu\tau} \neq 0$), or if the muons stored in a neutrino factory have a small branching to ν_τ, e.g. due to $\varepsilon^s_{\mu\tau} \neq 0$ or $\varepsilon^s_{e\tau} \neq 0$. In the first case, a ν_τ detector at around the first oscillation maximum would be required because the ν_τ flux first has to be generated by oscillation from ν_μ; in the second case, a ν_τ *near* detector would be optimal due to the higher flux at the near site.

From this analysis, we conclude that an ECC detector to look for τ's produced through $\nu_e \to \nu_\tau$ does not improve the expected IDS-NF baseline setup sensitivity to NSI in propagation. A thorough study of the impact of $\nu_\mu \to \nu_\tau$ data is lacking, though. We do not expect, however, these data to have a striking impact on the sensitivity, due to unitarity of the PMNS matrix in models in which only NSI in matter are considered.

C. Sterile neutrinos

Even though sterile neutrinos do no longer receive as much attention nowadays as before the publication of the MiniBooNE results, they are still a viable possibility, motivated by the fact that neutral singlets ν_s appear in many models of new physics. If they are light, the neutrinos produced in a neutrino factory may have a small admixture of ν_s, while heavy ν_s (such as right-handed Majorana neutrinos in type-I see-saw models) would manifest themselves in the form of a non-unitary mixing matrix of the light neutrinos.

In the case of one light ν_s, a recent study [11] shows that the $\nu_\mu \to \nu_\tau$ appearance channel (mostly disregarded up to now; see, however, Ref. [12]), measured with a magnetized ECC, is extremely important when combined to $\nu_\mu \to \nu_\mu$ to measure some of the parameters of the model, and in particular some of the new CP-violating phases. On the other hand, the silver channel $\nu_e \to \nu_\tau$ is only of limited impact when added to the golden channel $\nu_e \to \nu_\mu$, although it is useful to solve some of the many degeneracies in the parameter space.

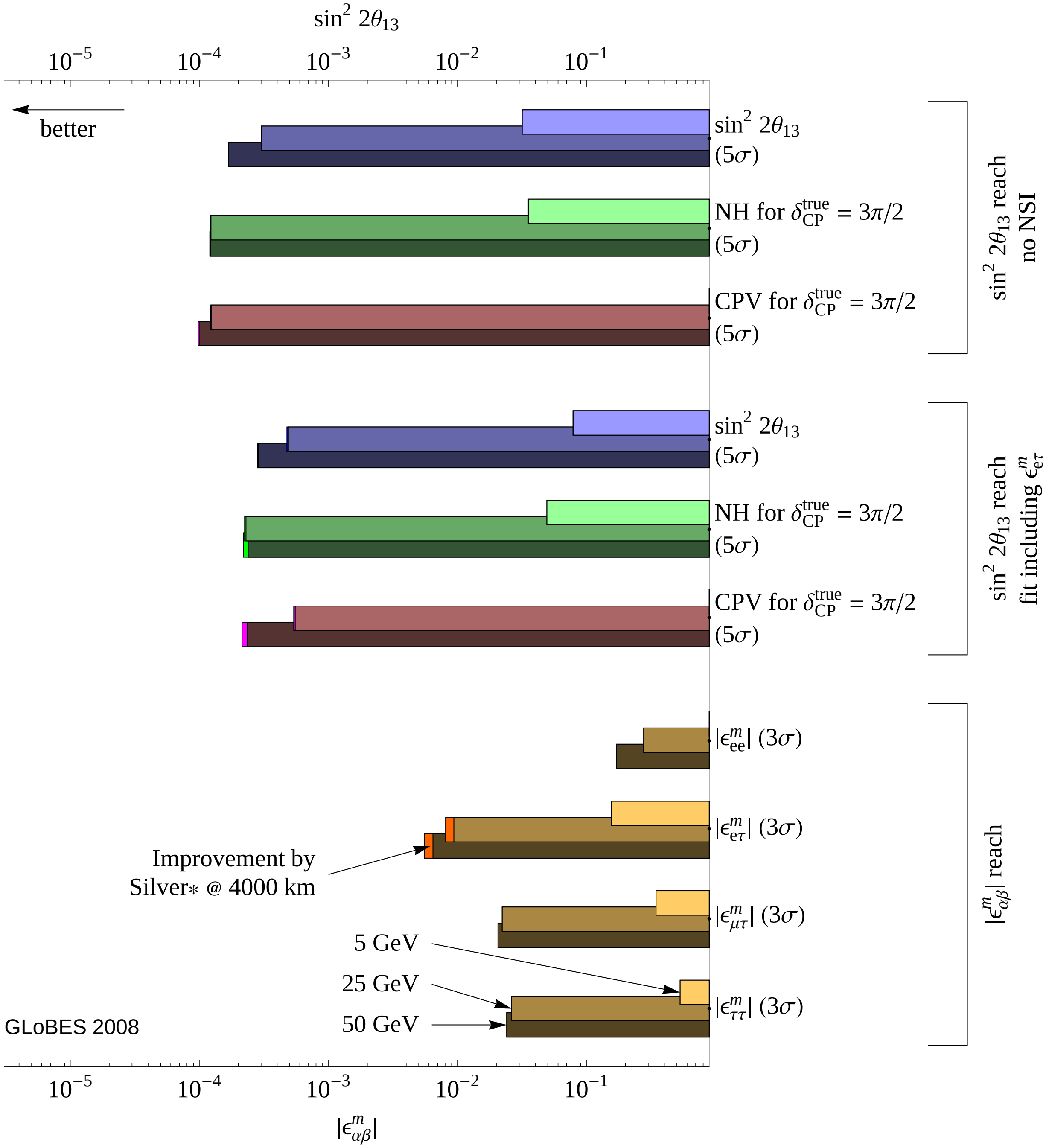

FIG. 1: Summary of the neutrino factory performance with and without the presence of non-standard interactions. The IDS-NF setup with two MIND detectors at $L_1 = 4\,000$ km, $L_2 = 7\,500$ km was used, and the "true" parameter values $\sin^2 2\theta_{13} = 0.001$ and $\delta_{\rm CP} = 3\pi/2$ were assumed. The plot shows that sensitivities are poor at $E_\mu = 5$ GeV (light bars), but increase dramatically at $E_\mu = 25$ GeV (medium light bars). The benefit from increasing E_μ further to 50 GeV (dark bars) is only marginal, as is the benefit from including a silver channel detector. Figure taken from [4]; see that paper for details.

A criticism to the use of magnetized ECC to study the $\nu_\mu \to \nu_\tau$ channel is that the scanning load could be too high for this analysis to be realistic. However, it has been found that the scanning load for an emulsion detector at $L > 1\,000$ km is not huge: O(500) events per kton per year with a 2×10^{20} flux are expected , for perfect efficiency. Adding a similar number of background events, this scanning load is compatible with

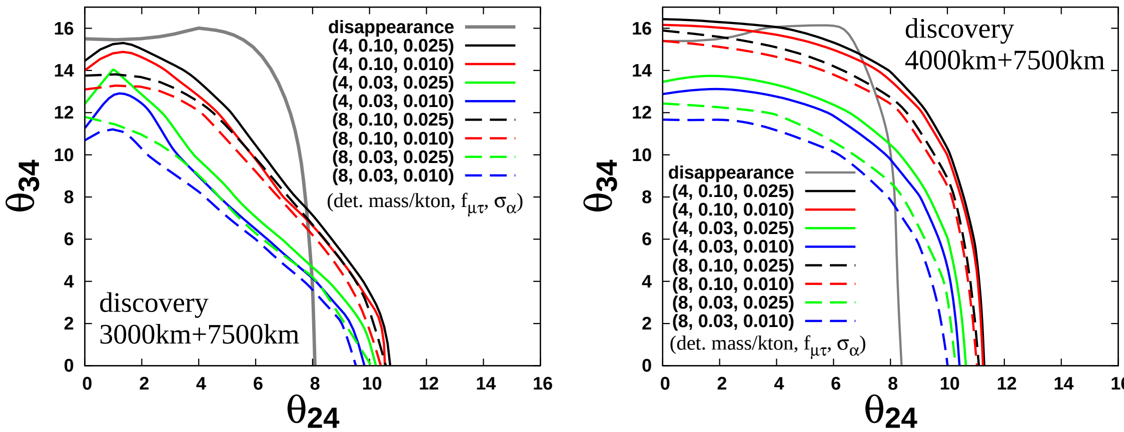

FIG. 2: *Left (right) panel: Dependence of the excluded region in the (θ_{24}, θ_{34})-plane on the systematic errors $f_{\mu\tau} \equiv f_j$ and σ_α for the discovery channel ($\nu_\mu \to \nu_\tau$) as well as the MECC detector mass at the 50 GeV (20 GeV) neutrino factory, where the excluded regions are by the discovery channel only. The solid (dashed) lines assume 4 kton (8 kton) for the tau detector mass. The solid gray line, which stands for the excluded region by the ν_μ disappearance channel, is also shown.*

extrapolation for present capabilities

Notice that for standard three-family oscillation and in models with NSI in propagation, due to the unitarity of the PMNS matrix, a good knowledge of the golden and the disappearance channel (both studied at MIND) should be enough to explore the whole parameter space. This, however, is not the case in models in which the 3×3 PMNS matrix is not unitary. In sterile neutrino models, for example, since we are not able to study the $\nu_\mu \to \nu_s$ appearance channel(s), the information that can be extracted from the ν_μ disappearance channel and the $\nu_\mu \to \nu_\tau$ channel are not identical. The same would happen in extensions of the standard model in which NSI are considered both in propagation and production, such as to violate unitarity of the PMNS matrix.

From the analysis of Ref. [11] we conclude that the combination of the IDS-NF baseline setup (with two MINDs) with one or two magnetized ECC increase significantly the potential of the Neutrino Factory to measure all the parameter space of the (3+1)-neutrino model and, in particular, to increase its CP-violation discovery potential. However, it has been shown that the present design of the magnetized ECC is not optimized and that a dedicated study of the detector to look for new physics is mandatory (see next section).

The optimal location for a long baseline τ-detector to study sterile neutrinos is not clear, yet. Whereas a detector whose purpose is the study of the silver channel in the framework of the three-family model or NSI in propagation is optimally located around the intermediate IDS-NF baseline (see ISS Final Report and Ref. [4]), it seems that to study (3+1) sterile neutrinos to put the magnetized ECC detector at the Magic Baseline could be more convenient. This is particularly true for searches of CP-violating signals. At the Magic Baseline, indeed, the standard three-family CP-violating effect vanishes, and therefore if CP-violation is observed this is clearly pointing out the existence of physics beyond the standard model (either new particles, such as the sterile neutrinos, or new effective operators, such as in NSI). Notice that the $\nu_\mu \to \nu_\tau$ statistics at the Magic Baseline is still large (of O(500) events for 1 kton MECC with perfect efficiency and 2×10^{20} useful muons per year).

III. TECHNOLOGICAL OPTIONS FOR τ-DETECTORS

The technology for tau-detectors has not been fixed yet. The liquid argon technology should be studied further (something compatible with the time scale of a Neutrino Factory). Furthermore, the impact of systematics errors in the magnetized emulsion technique (MECC) is shown to be very important, see Fig. 2.

In the figure, the sensitivity to two parameters of a model with three active and one sterile neutrino (the "3+1" model) using the $\nu_\mu \to \nu_\tau$ channel is shown. The dashed gray line refers to the sensitivity to those parameters achievable using two 50 kton MIND detectors: one at an intermediate baseline, $L = 3000 - 4000$ km, and the second at the Magic Baseline. In the two panels, we show the sensitivity for a 50 GeV muon Neutrino Factory (left) and a 20 GeV muon Neutrino Factory (right). It is clear from the left panel that a huge increase in the sensitivity of the $\nu_\mu \to \nu_\tau$ channel is achieved if the uncorrelated systematic errors are reduced from 10%(black solid line) to 3% (green solid line). This improvement is actually much more important than an increase in the MECC detector mass from 4 kton (green solid line) to 8 kton (green dashed line).

This systematic error is taking into account in a non-detailed way systematics induced by normalization of the flux and cross-sections. Both are expected to be better known after the first OPERA phase. Moreover, $\nu_\tau N$ cross-sections must be studied with a near detector, as it happens for the $\nu_\mu N$ one. This means that these sources of systematics can be strongly reduced. A study of the possible improvement of the sensitivity with a better design of the τ-detector in the framework of NSI extensions of the standard model is lacking.

IV. CONCLUSIONS & RECOMMENDATIONS

In this note, we have discussed the potential of an ECC, added to the IDS-NF baseline setup (with two MIND detectors located at $L \sim 4000$ km and at the Magic Baseline), in three models: the standard three-family oscillation scenario; an extension of the SM with Non-Standard Interactions in matter; and an extension of the SM with one extra light singlet fermion (the so-called 3+1 sterile neutrino model). In the first two cases, the ν_τ detector does not improve the potential of the IDS-NF baseline setup to measure the oscillation parameters or to uncover new physics effects in neutrino oscillations. The reason is that, due to the large mixing in the μ-τ sector, most effects that are present for τ-neutrinos, will have a similar impact also for μ-neutrinos. In these models, the τ-detector could only serve as a tool for resolving parameter degeneracies. This, however, could be also achieved combining the Golden and Disappearance channels and data from two different baselines $L = 4\,000$ km and $L = 7\,500$ km. We must remind that a comparison of the potential of the IDS-NF baseline setup and the same setup with an additional τ-detector to measure the θ_{23}-octant in the standard three-family oscillation model is missing, though (see Ref. [5]).

In the case of the (3+1)-sterile neutrino model, studied in Ref. [11], the availability of the $\nu_\mu \to \nu_\tau$ data using a magnetized ECC has been shown to be extremely important to measure the whole parameter space of the model and, in particular, to study CP-violating phases different from the standard three-family oscillation one, δ.

There may also be a physics case for ν_τ detection if new physics should manifest itself in the ν_τ detection process, or if non-standard couplings of ν_μ, ν_e to τ leptons or of ν_τ to muons and electrons should exist. However, non-standard contributions to the ν_τ detection process would require a ν_τ detector at a long baseline (e.g. $4\,000$ km), while non-standard τ and ν_τ production can be most efficiently observed in a ν_τ near detector.

The outcome of this short review is that it is very difficult, at the present stage, to draw a final conclusion on the increase in the Neutrino Factory physics potential to discover new physics if a τ-detector is added to the IDS-NF baseline setup. It is also far from clear which detector technology would be optimal: a good knowledge of the ECC technology will be available only after some years of OPERA data taking; it is not clear if a magnetized ECC, important to increase the ECC statistics, is feasible; the liquid Argon technology has not been studied in detail. Eventually, the technology to be used if a near τ-detector should be built could be completely different from what proposed up to now: due to the high neutrino flux at the near site if exposed to a Neutrino Factory beam, more powerful techniques than what suggested for a large detector could be used, since a smaller detector mass could be sufficient.

In view of these arguments, we suggest that the ECC τ-detector is *not* to be included in the IDS-NF *baseline* setup due to the absence of a compelling physics case and, given the present very preliminary status of the detector design. This does not exclude the option that a ν_τ detector (not necessarily based on the ECC technology) is added to the neutrino factory at a *later stage* of the project if unexpected results from the LHC or from the neutrino factory itself should create a physics case for it.

However, we think it is mandatory to further pursue the study of the potential of such a detector, especially in view of the fact that we do not know what new physics may be out there. Having access to more flavors can only increase the discovery potential of the Neutrino Factory. Notice, eventually, that if θ_{13} results to be large (see solar, atmospheric and MINOS results), part of the statistical problems of the τ-channels become less relevant. At the same time, the main motivation for a Neutrino Factory would become the search for new physics beyond the Standard Model, and therefore the option of an increased flavor sensitivity becomes extremely interesting.

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